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THE BAUSCHINGER EFFECT IN 6-6-2 TITANIUM ALLOY AND ITS INFLUENCE ON ADVANCED ARTILLERY PROJECTILES

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MECHANICS AND STRUCTURES BRANCH

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ABSTRACT

In this report, the Bauschinger effect in 6-6-2 titanium alloy is evaluated and an illustration is given to demonstrate its importance in the design and reliability of the Army's advanced artillery projectiles. The tension-compression specimens, fabricated from the recovered projectiles, are loaded to compression to a specified plastic range, followed by tension after unloading. The experimental results indicate that the original yield strength of the material is greatly reduced due to reverse loading.

Keywords: Titanium alloys; Aluminum/Vanadium/Tin; XM-785 projectiles.

NOMENCLATURE

BEF	Bauschinger effect factor
C	Compression
E	Young's modulus
P	Load
R	Residual
T	Tension
x, y	Rectangular coordinates
ε^{C}_{Y}	Strain at yield in compression
σ_x	Normal stress in x direction
σ_y	Normal stress in y direction
σ_Y	Yield stress in tension or compression

CONTENTS

INTRODUCTION

The Bauschinger effect may be defined as a phenomenon by which plastic deformation of a polycrystalline material causes a reduction in yield strength upon reloading in a direction opposite to the original direction. This characteristic of plastic flow results from the inhomogeneity of plastic flow on the microscopic level.[1,2]

(to p. ii)

Milligan et al.,[3] reported that a number of investigators have shown, experimentally, the Bauschinger effect to exist in single crystals of ferrous and nonferrous materials. Welter[4,5] did extensive study on Bauschinger effects of various alloys subjected to dynamic torsional and axial loadings. Milligan[6] reported the influence of the Bauschinger effect on reverse yielding of thick cylinders used for gun tubes. Applications arise in military weapons where the Bauschinger effect in materials is of considerable importance. For example, in manufacturing gun tubes, they are prestressed into the plastic range to induce beneficial residual compressive stress. In artillery projectiles, the cylindrical walls are subjected to severe compressive stress in the gun barrel, followed by tensile stress at barrel exit. Most projectiles are fabricated from structural steel with a relatively simple design configuration. Some advanced projectiles are fabricated from 6-6-2 titanium alloy with more complicated geometry where local plastic deformation is possible.

The Army's advanced artillery projectiles, made of 6-6-2 titanium alloy, contain many locations of high stress concentrations such as holes and abrupt changes in sections. These critical locations could be subjected to severe compressive stress beyond the elastic range in the gun barrel followed by tensile stress at barrel exit. As a result of the reverse loading, there is a possibility that some of these critical locations in a projectile could be stressed beyond the tensile yield strength. To date, no data is available concerning the Bauschinger effect in this 6-6-2 titanium alloy specifically developed for the Army's advanced artillery system. In this report, the Bauschinger effect in 6-6-2 titanium alloy is evaluated, and an illustration is given to demonstrate its importance in the design and reliability of the Army's advanced artillery projectiles.

DESCRIPTION OF THE MATERIAL

The material used for testing was 6-6-2 titanium alloy in the form of recovered projectiles XM-785.* The chemical composition and the mechanical properties of the material† are listed in Tables 1 and 2, respectively.

*Fabricated by Chamberlain Manufacturing Corp., Waterloo, Iowa.

†Processed by Oregon Metallurgical Corp. (ORMET), Albany, Oregon.

1. POLAKOWSKI, N. H., and RIPLING, E. J. *Strength and Structure of Engineering Materials.* Ch. 6, Prentice-Hall, 1966.
2. MARGOLIN, H., HAZAVEH, R., and YAGUCHI, H. *The Grain Boundary Contribution to the Bauschinger Effect.* Scripta Metallurgica, v. 12, 1978, p. 1141-1145.
3. MILLIGAN, R. V., KOO, W. H., and DAVIDSON, T. E. *The Bauschinger Effect in a High-Strength Steel.* J. Basic Engineering, Trans. ASME, June 1966, p. 480-488.
4. WELTER, G. *Dynamic Torsion of Metals and Alloys Used in Aircraft Construction.* Metallurgica, Part I, February 1949, p. 188-190; Part II, March 1949, p. 253-256; Part III, April 1949, p. 313-315.
5. WELTER, G. *Micro- and Macro-Deformations of Metals and Alloys Under Longitudinal Impact Loads.* Metallurgica, Part I, September 1948, p. 287-292; Part II, October 1948, p. 328-330; Part III, November 1948, p. 13-17.
6. MILLIGAN, R. V. *The Influence of the Bauschinger Effect on Reverse Yielding of Thick-Walled Cylinders.* WVT-7036, Benet R&E Lab., Watervliet Arsenal, October 1970.

Table 1. CHEMICAL COMPOSITION (LOT A4, HEAT NO. D9840)

Weight (%)								
Al	V	Sn	Fe	Cu	C	N	H_2	O_2
5.50	5.48	1.97	0.702	0.494	0.027	0.016	0.0013	0.18
Yttrium			Others Total			Ti		
Less Than 0.003			Less Than 0.3			Balance		

Table 2. TENSILE TEST (LOT A4, HEAT NO. D9840)

	Manufacturer	Present Test
Yield Strength (0.1% offset) (psi)	170,000	168,000
Ultimate Strength (psi)	178,900	177,000
Young's Modulus (psi)		18.2×10^6
Reduction of Area (%)	31.1	24
Elongation (%)	11	11
Strain at 0.1% Offset Stress		0.01

The specimen used by the manufacturer for testing was fabricated from the same material, Lot A4, Heat No. D9840, with the same heat treatment condition as in the projectiles, whereas the specimen used for the present testing was machined from the recovered projectile from the same material lot. Figures 1 and 2 show the specimen configuration used for testing. The photomicrograph of the material is shown in Figure A-1 of the Appendix. Sample graphs of the tensile test are shown in Figures A-2 and A-3 of the Appendix. A description of the strain gages, fixtures, and testing is given in the Experimental Procedure Section.

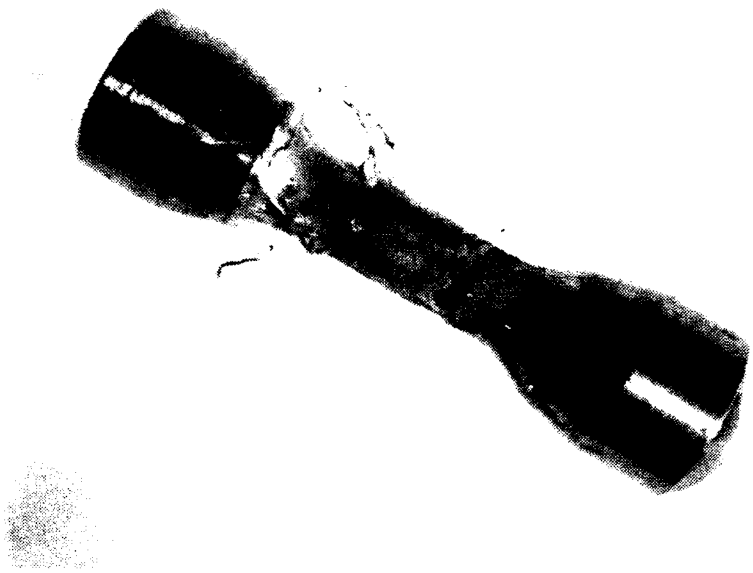
EXPERIMENTAL PROCEDURE

The specimens used for testing were machined from the motor body of recovered XM-785 projectiles. Their configuration and dimensions are shown in Figures 1 and 2. The portion of the motor body used for preparing the specimens is shown in Figure 3. This nonstandard specimen has been used to test various materials at the U.S. Army Materials Technology Laboratory (MTL) for many years. It is to be noted that this is the largest specimen that can be prepared from the walls of most types of artillery projectiles.

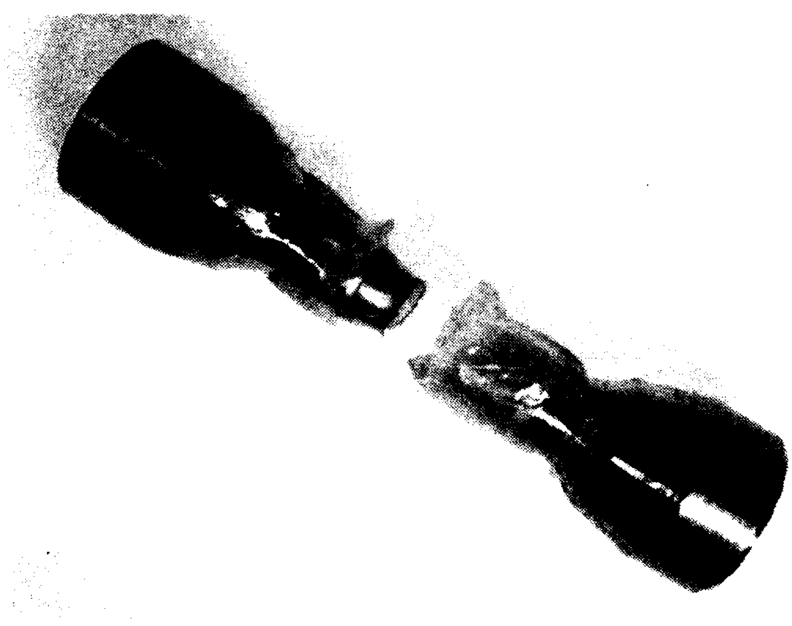
Three separate strain gages (EP-08-062AQ-350 from Micro-Measurements Division, Measurements Group, Inc.) were bonded to each specimen by epoxy adhesive (EPY-150 from BLH Electronics). The gages, placed at equal distance (120 degrees) around the midcircumference of the specimen, were used to record normal strains individually along the longitudinal axis of the specimen. These gages have special annealed constantan foil with tough, high elongation polymide backing. They are used primarily for measurements of large, postyield strains. The maximum range of strain for the gages used in the present test is ±10%.

A set of special grips* and load-alignment fixtures were used to apply an axial load to the specimens by the testing machine (MTS, 20,000 lb capacity, hydraulic closed loop).

*The grips were provided by the Materials Dynamics Branch, Materials Reliability Division, MTL.

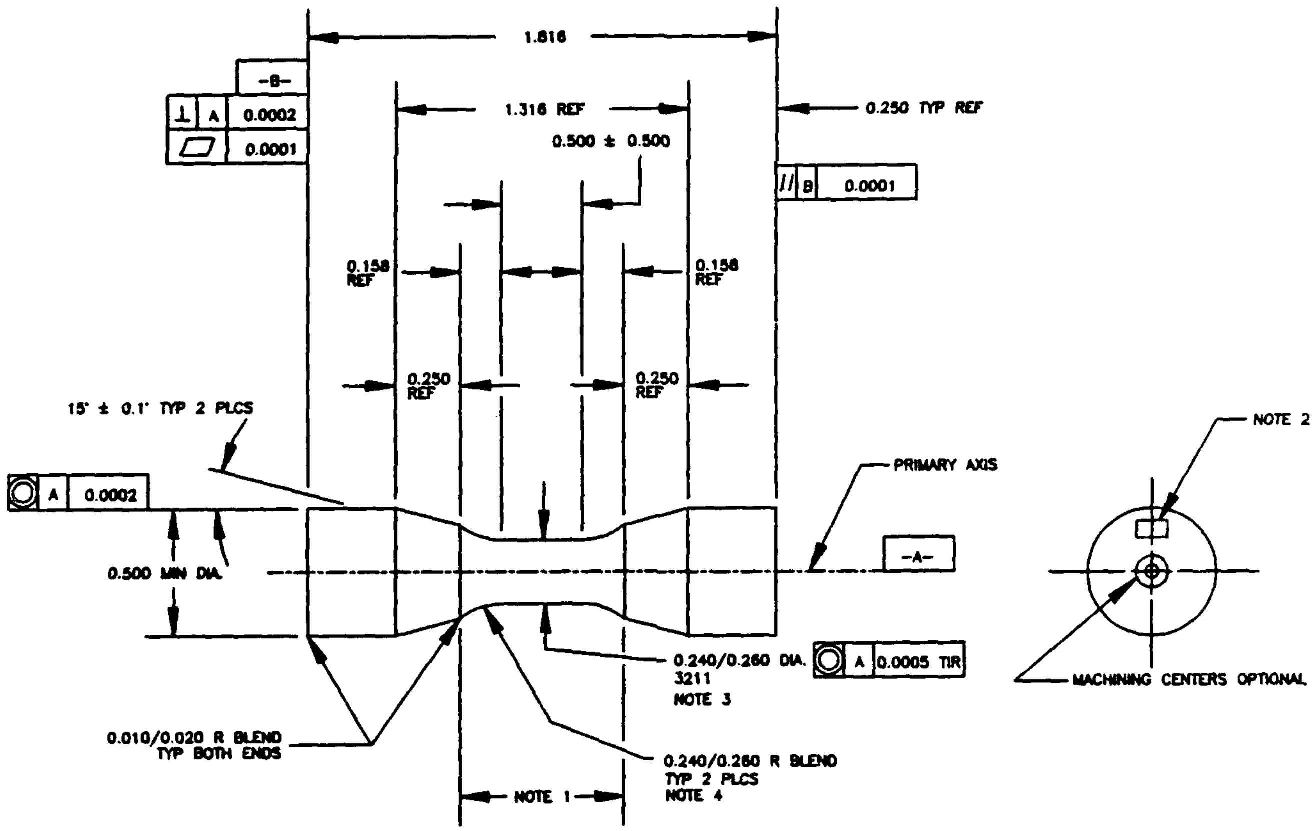


(a) With Strain Gages Attached



(b) Fractured Specimen After Tensile Testing

Figure 1. The tension-compression specimen.



NOTES:

1. FOR BERYLLIUM ONLY:
   ETCH TO FINISH DIMENSIONS 0.004/0.005 PER SURFACE ALONG LENGTH SHOWN ONLY. DO NOT ETCH TAPER.
2. MARK APPLICABLE SPECIMEN IDENTIFICATION NUMBER III 1/8" CHARACTERS WITH BLACK EPOXY INK OR ELECTRO-ETCH.
3. HOLD SYMMETRICAL WITH RESPECT TO ENDS REGARDLESS OF LENGTH DIMENSIONS.
4. FILLET RADII MUST BE TANGENT, NOT UNDERCUT.
5. 32 RMS UNLESS SPECIFIED.

Figure 2. The tension-compression specimen.

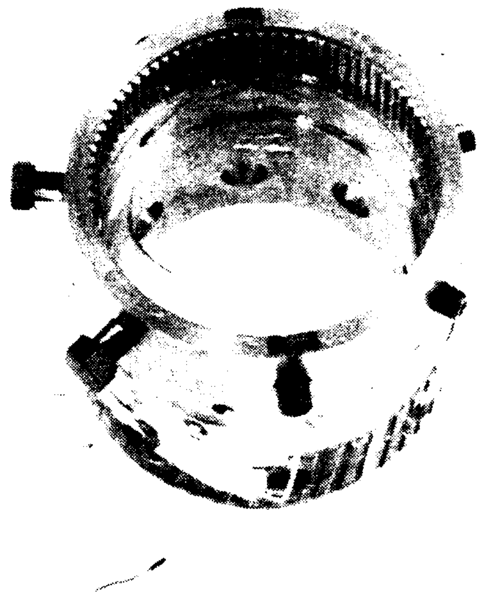


Figure 3. The portion of the motor body from XM-785 projectile used for preparing specimen.

Figure 4 shows the exploded view of the grips with a strain-gaged specimen next to it. The split collet "a," has a taper of included angle of 30 degrees, which transmits axial load to the specimen during tensile loading. The solid cylinder "c," and the pair of wedges "d," transmit axial load to the specimen during compressive loading. One of the threaded collet holders "b," is attached to the crosshead of the machine through a load cell recording axial loads. The other collet holder is attached to the hydraulic ram of the machine through a special load-alignment fixture (figure not shown). Figure 5 shows a load-alignment fixture used in Ref. 3 where provision for alignment exists for both ends of the specimen. The alignment fixture used in the present test is similar to that in Ref. 3 with the exception that the alignment is provided only at one end (bed of the testing machine) of the specimen. The function of this fixture is to prevent the hydraulic ram from moving sideways so that the transverse motion of the specimen is minimized.

Initial load alignment was accomplished with a split test specimen. One of the specimens was cut at the middle into two pieces for this purpose and secured by the special grips. Then, the eccentricity between the axes of loading was minimized by adjusting the attachments of the testing machine, load cell, and load-alignment fixture. Final load alignment was accomplished with a test specimen containing three strain gages. The readings from the three separate strain gages on each specimen were used to adjust and monitor the eccentricity in loading.

A set of three specimens was tested to record the loads versus strains. The loading was compressive to a specified plastic range, followed by tensile after unloading. The graphs for testing and alignment check are shown in Figures A-4 through A-19 in the Appendix. The mechanical properties and the Bauschinger effect factor (BEF) calculated from those graphs

are shown in Tables 3 through 5. It is to be noted that the values of strain and Young's modulus in the tables are neither used nor discussed in the report. They are reported here for documentation only. The readings by the three separate strain gages mounted on each specimen were noticeably different, especially in the plastic range. These were probably caused partly by gage mounting error, and mostly due to growing eccentricity during compressive loading; so, for each test, an average of three gage readings was computed to obtain the desired quantities. Several additional specimens were tested; because of either gage failure or very large eccentricity in loading, they are not reported here.

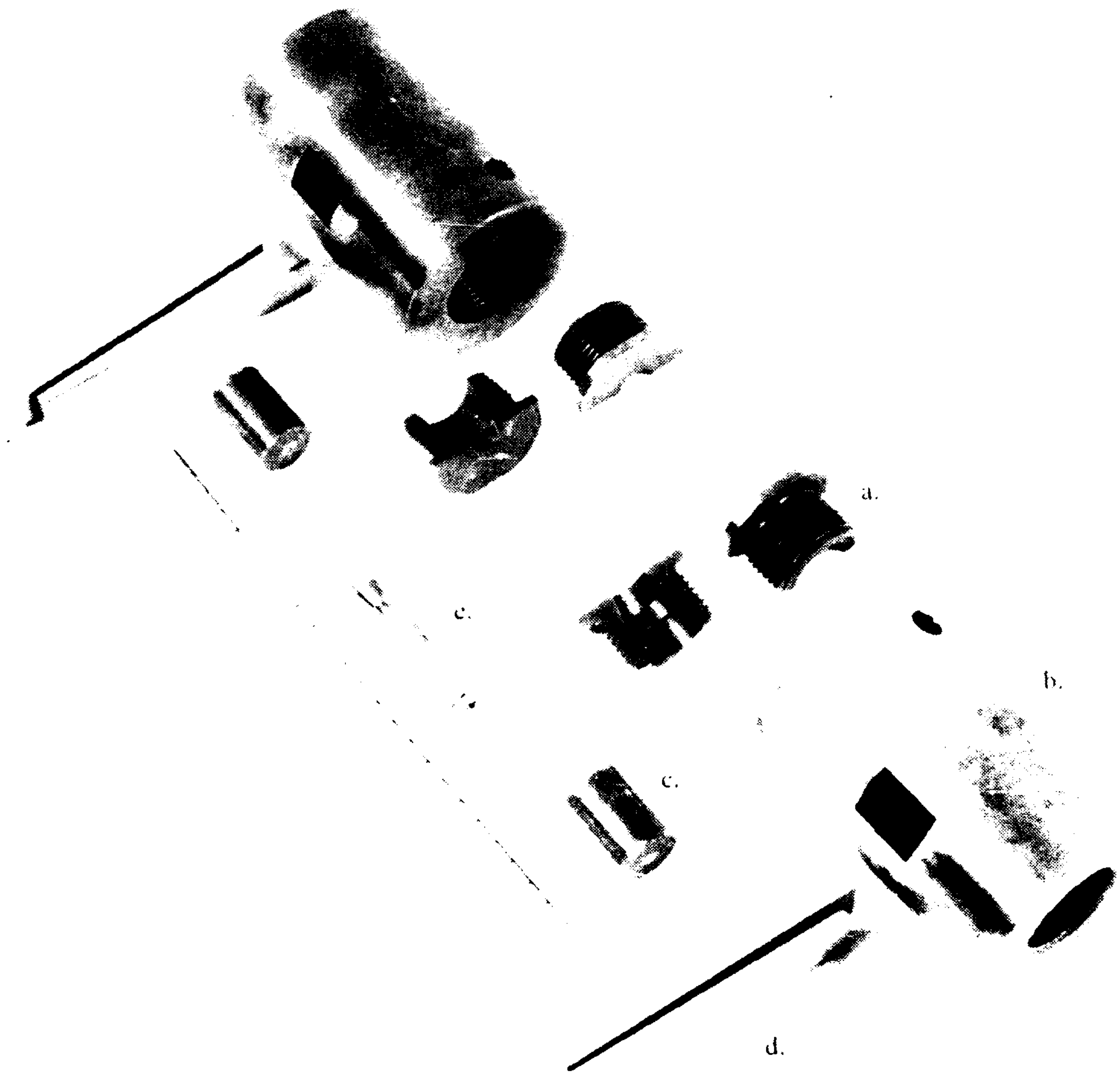


Figure 4. The special grips to hold the specimen showing (a) split collet, (b) threaded collet holder, (c) solid cylinder, (d) pair of wedges, and (e) specimen.

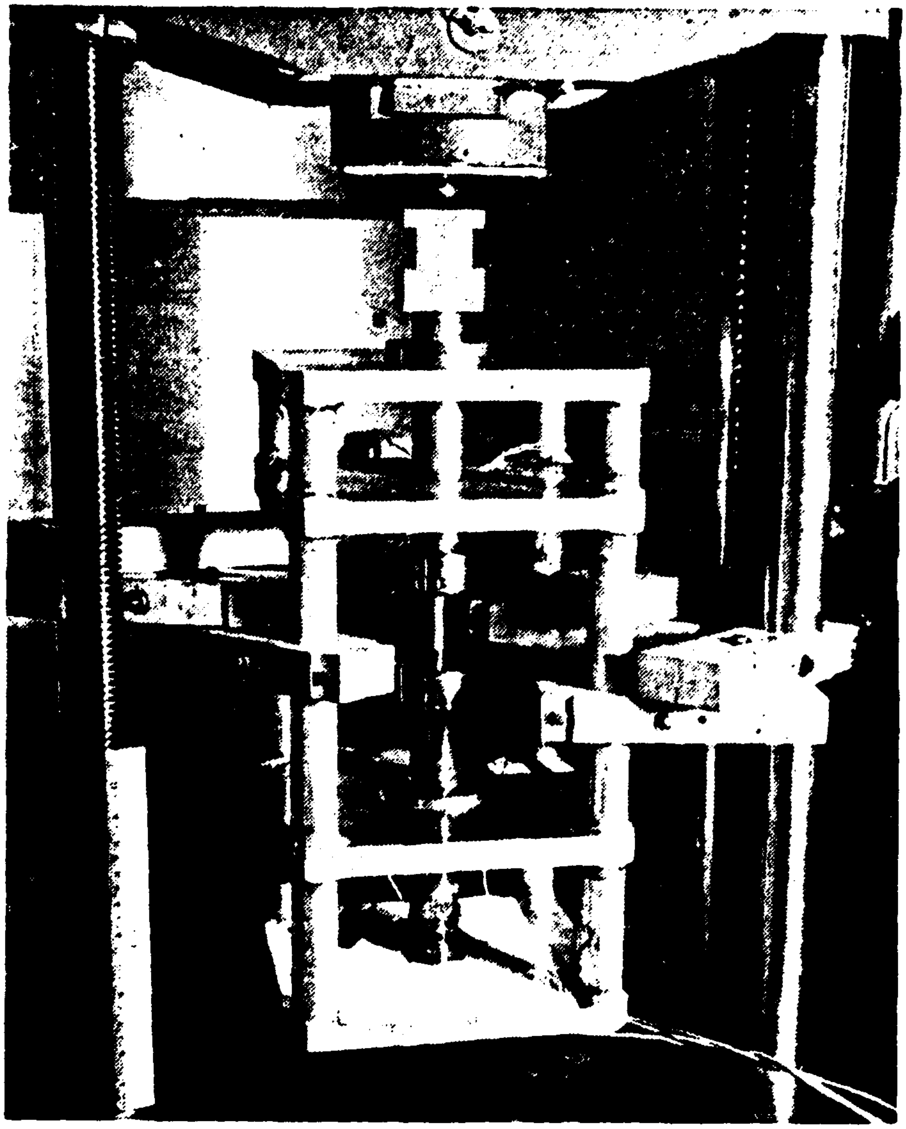


Figure 5. Load-alignment fixture (Ref. 3).

Table 3. THE TEST DATA AND BAUSCHINGER EFFECT FACTOR FOR SPECIMEN NO. 1

Motor Body A4-30, Specimen No. 1, Specimen Diameter = 0.251 inches

	Gage #1	Gage #2	Gage #3	Average
σ_Y^C (0.1%) (lb/in.^{2})	176,000	179,000	177,000	177,000
σ_Y^C (0.2%) (lb/in.^{2})	179,000	182,000	179,000	180,000
ε_Y^C (0.1%)	0.011	0.011	0.0103	0.011
ε_Y^C (0.2%)	0.012	0.012	0.0115	0.012
σ_Y^T (0.1%) (lb/in.^{2})	63,000	61,000	67,000	64,000
σ_Y^T (0.2%) (lb/in.^{2})	86,000	85,000	83,000	85,000
Compressive Plastic Prestrain	0.023	0.017	0.026	0.022
E^c (lb/in.^{2})	18×10^6	19×10^6	19×10^6	18.7×10^6
BEF (0.1%)	0.356	0.339	0.366	0.35
BEF (0.2%)	0.48	0.467	0.463	0.47

Table 4. THE TEST DATA AND BAUSCHINGER EFFECT FACTOR FOR SPECIMEN NO. 15

Motor Body A4-30, Specimen No. 15, Specimen Diameter = 0.253 inches

	Gage #1	Gage #2	Gage #3	Average
σ_Y^C (0.1%) (lb/in.^{2})	Gage #1 was Debonded	177,000	181,000	179,000
σ_Y^C (0.2%) (lb/in.^{2})		188,000	185,000	183,000
ε_Y^C (0.1%)		0.011	0.011	0.011
ε_Y^C (0.2%)		0.012	0.012	0.012
σ_Y^T (0.1%) (lb/in.^{2})		64,000	66,000	65,000
σ_Y^T (0.2%) (lb/in.^{2})		87,000	90,000	88,000
Compressive Plastic Prestrain		0.0165	0.009	0.013
E^c (lb/in.^{2})		18.2×10^6	19.9×10^6	19.1×10^6
BEF (0.1%)		0.359	0.363	0.36
BEF (0.2%)		0.478	0.484	0.48

Table 5. THE TEST DATA AND BAUSCHINGER EFFECT FACTOR FOR SPECIMEN NO. 16

Motor Body A4-30, Specimen No. 16, Specimen Diameter = 0.252 inches

	Gage #1	Gage #2	Gage #3	Average
σ_Y^c (0.1%) (lb/in.^{2})	180,000	184,000	182,000	182,000
σ_Y^c (0.2%) (lb/in.^{2})	185,000	187,000	186,000	186,000
ϵ_Y^c (0.1%)	0.0125	0.011	0.01075	0.0114
ϵ_Y^c (0.2%)	0.01375	0.01225	0.012	0.0127
σ_Y^T (0.1%) (lb/in.^{2})	70,000	72,000	72,000	71,000
σ_Y^T (0.2%) (lb/in.^{2})	90,0003	100,000	94,000	95,000
Compressive Plastic Prestrain	0.01	0.0065	0.0075	0.008
E^c (lb/in.^{2})	18.3×10^6	18.9×10^6	18.9×10^6	18.7×10^6
BEF (0.1%)	0.389	0.391	0.396	0.39
BEF (0.2%)	0.486	0.534	0.505	0.51

RESULTS AND DISCUSSION

The BEF is defined as the ratio of the yield stress in tension (σ_Y^T) after unloading to the yield stress in compression prior to unloading (σ_Y^c). Referring to Figure 6, the BEF (0.1%) is given by

$$\text{BEF (0.1\%)} = \frac{\sigma_Y^T\,(0.1\%)}{\sigma_Y^c\,(0.1\%)} \tag{1}$$

The notation (0.1%) is used to indicate 0.1% offset yield stress.

The BEF for various compressive plastic prestrain are shown in Tables 3 though 5. Figure 7 shows the plot of BEF versus compressive plastic prestrain for 0.1% and 0.2% offset yield stress. It indicates a decrease of the BEF with increasing amount of compressive plastic prestrain. The BEF decreases very rapidly at the initial stages of the compressive plastic prestrain, but appears to remain constant after 2.0% of compressive plastic prestrain.

The practical implications of the Bauschinger effect in 6-6-2 titanium alloy is evident from this figure. For example, a compressive plastic prestrain of 2.0% results in a tensile yield strength which is about [illegible]% of the initial 0.1% offset compressive yield strength. For 0.2% offset yield strength, this is about 47%.

When initiation of yielding is one of the modes of failure in a structural component, loss in yield strength could greatly reduce the load-carrying capability of the component upon

reverse loading. In order to demonstrate the influence of the Bauschinger effect on the load-carrying capability of a structural component, a simple illustration is given below.

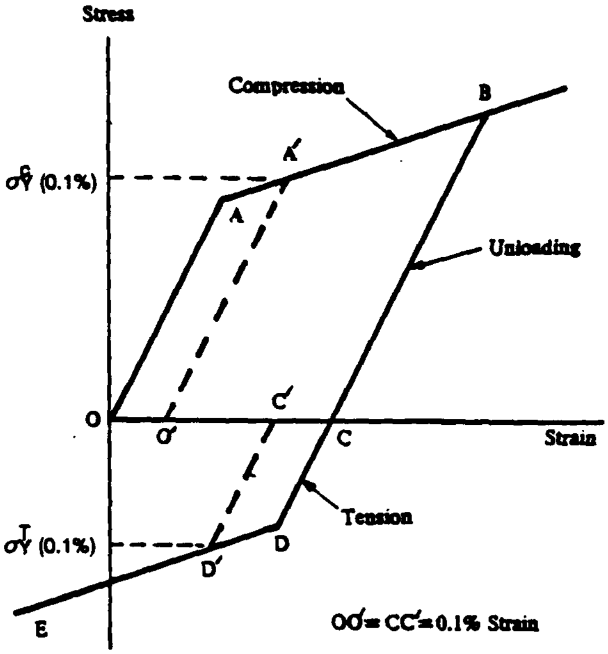


Figure 6. Diagram of stress versus strain to illustrate the definition of the Bauschinger effect factor.

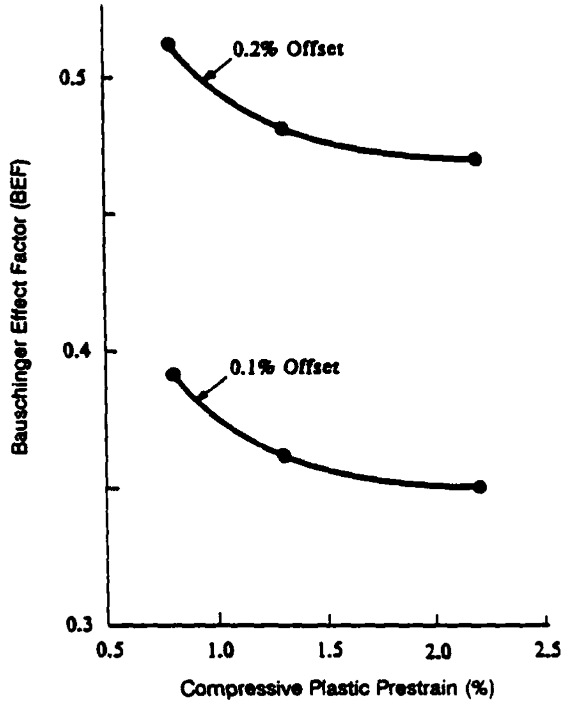


Figure 7. The Bauschinger effect factor versus compressive plastic prestrain.

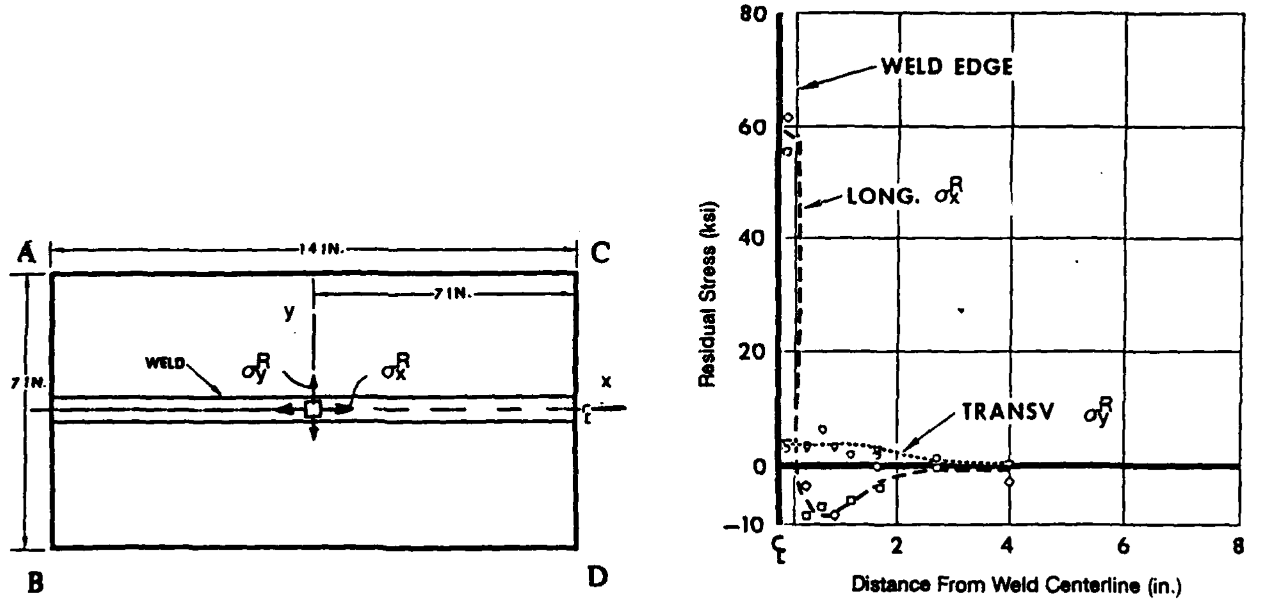
Consider a 0.2-inch-thick, butt-welded plate fabricated from 6-4 titanium alloy by gas tungsten-arc welding (Figure 8a). The alloy has a yield strength of 131 ksi, ultimate strength of 136 ksi, and elongation of 13.5%. The residual stresses caused by welding has been determined experimentally by Robelotto et al.[7] The residual normal stress in the longitudinal direction (x direction) σ_x^R, and in the transverse direction (y direction) σ_y^R, is shown in Figure 8b. These residual stresses are evaluated for the center of the plate to its edge in y direction. It is observed that at the center of the plate, the residual stress σ_y^R in the transverse direction is negligible compared to the residual stress σ_x^R in the longitudinal direction.

If a uniformly distributed tensile load of total magnitude P lb is now applied at the two edges, AB and CD, of the plate in x direction, then the condition for failure by yielding at the center of the plate is

$$[P / (7.0 \times 0.2) + \sigma_x^R] = \sigma_Y . \qquad (2)$$

7. ROBELOTTO, R., LAMBASE, J. M., and TOY, A. *Residual Stresses in Welded Titanium and Their Effects on Mechanical Behavior.* Welding Research, Supplement, July 1968, p. 289S-298S.

Substituting the values of the yield stress of the material and the residual stress at the center of the plate into Equation 2, the magnitude of load P to initiate yielding becomes 99,400 lb. In the absence of the residual stress, the magnitude of load P required to initiate yielding is 183,400 lb. Therefore, the presence of residual stress reduces the elastic load-carrying capability of the plate to 54% of the load that a residual stress-free plate could carry.



(a) The Butt-Welded Plate (Ref. 3) (b) The Residual Stress Distribution in the Welded Plate (Ref. 3)

Figure 8.

Similar severe residual stresses could develop in artillery projectiles due to torsional, compressive, and bending loads generated when the projectile is in the gun barrel. As a result, the load-carrying capability of the projectile could be greatly reduced upon barrel exit. Moreover, if the projectiles containing flaws in the critical locations are used at subzero temperatures, the failure could occur by brittle fracture.[8]

CONCLUSIONS

Experimental results indicate that the BEF in 6-6-2 titanium alloy specimens, prepared from recovered projectiles XM-785, decreases with increasing amount of compressive plastic prestrain. The BEF decreases very rapidly at the initial stages of the compressive plastic prestrain, but appears to remain constant after 2.0% of compressive plastic prestrain. A compressive plastic prestrain of 2.0% results in a tensile yield strength which is about 35% of the initial 0.1% offset compressive yield strength.

The load-carrying capability of advanced artillery projectiles, fabricated from 6-6-2 titanium alloy, could be greatly reduced upon barrel exit due to severe reverse loading (Bauschinger effect) in the gun barrel.

8. BORESI, A. P., and SIDEBOTTOM, O. M. *Advanced Mechanics of Materials.* Ch. 3-1, John Wiley and Sons, 1985.

ACKNOWLEDGMENTS

The author is grateful for the support and encouragement provided by Jiro Adachi of Massachusetts Institute of Technology Liaison Program, Cambridge, MA [formerly of Materials Reliability Division, U.S. Army Materials Technology Laboratory (MTL)], Carmine Spinelli, Jack Sacco, Harry Smith, and Bob Wilgus of Picatinny Arsenal, and Roger Gagne of Materials Exploitation Division, MTL. The author also deeply appreciates the assistance provided by the Materials Testing and Evaluation Branch of MTL.

APPENDIX.

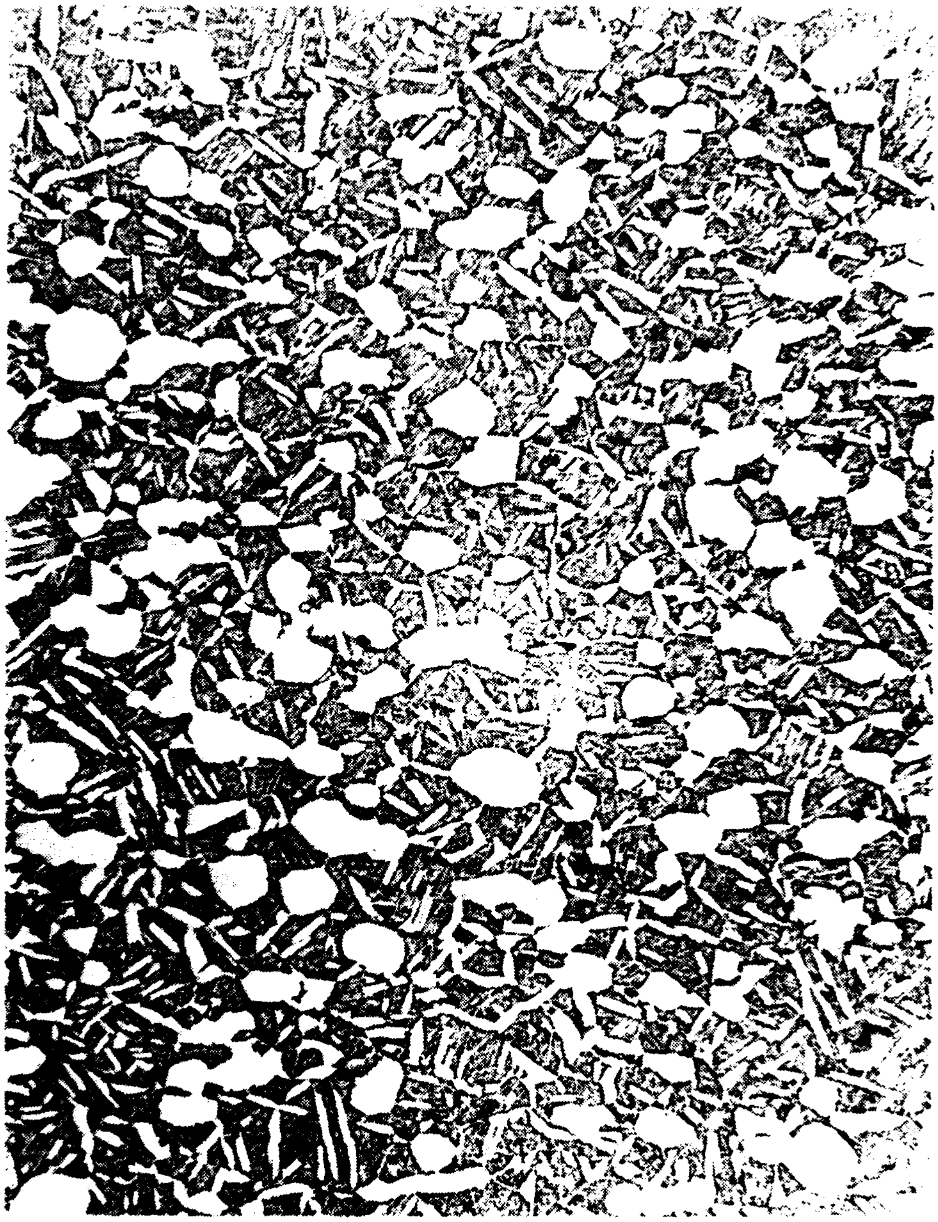


Figure A-1. Photomicrograph of 6-6-2 titanium alloy taken from recovered projectile, Mag. 1000X.

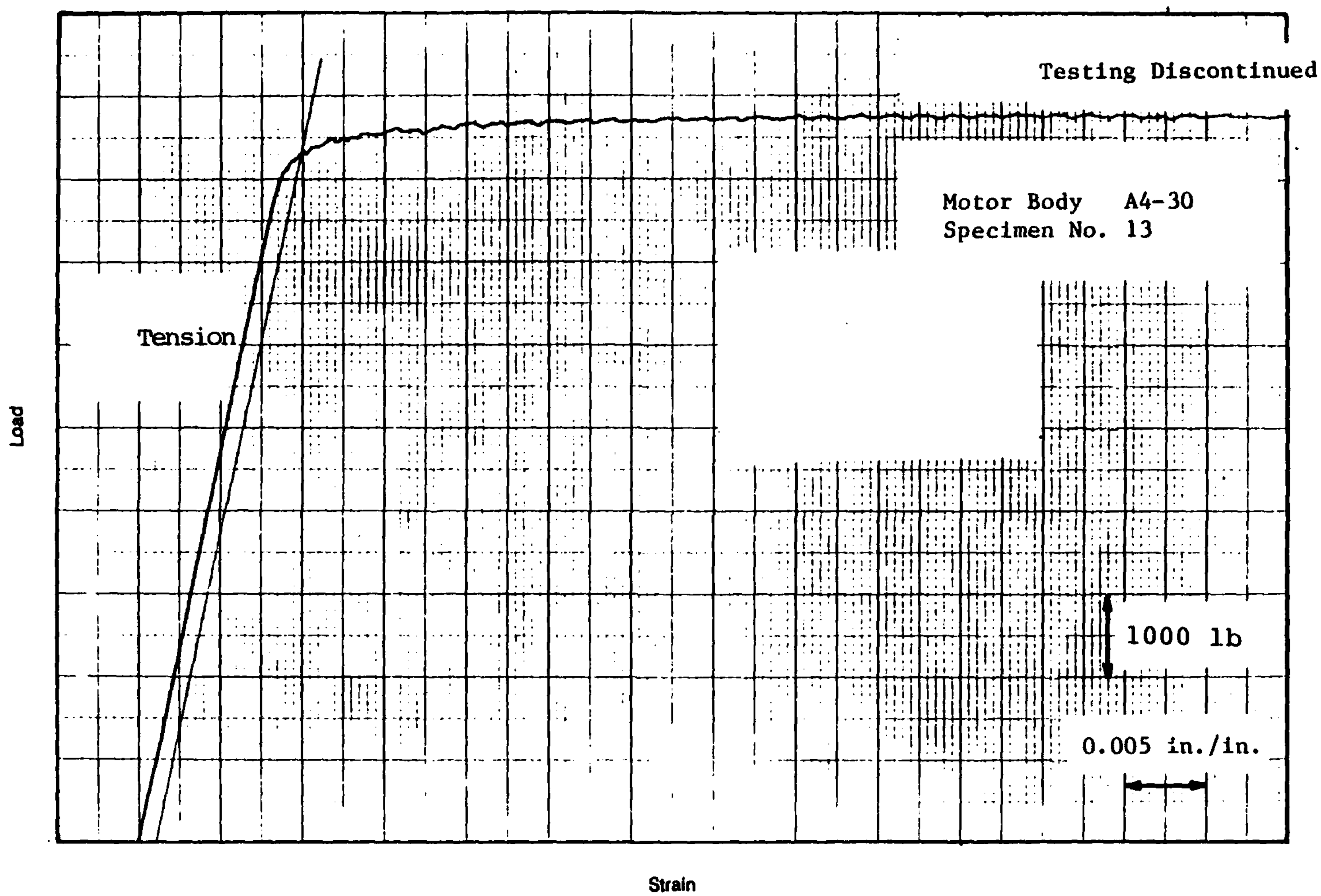


Figure A-2. Tension test (specimen no. 13).

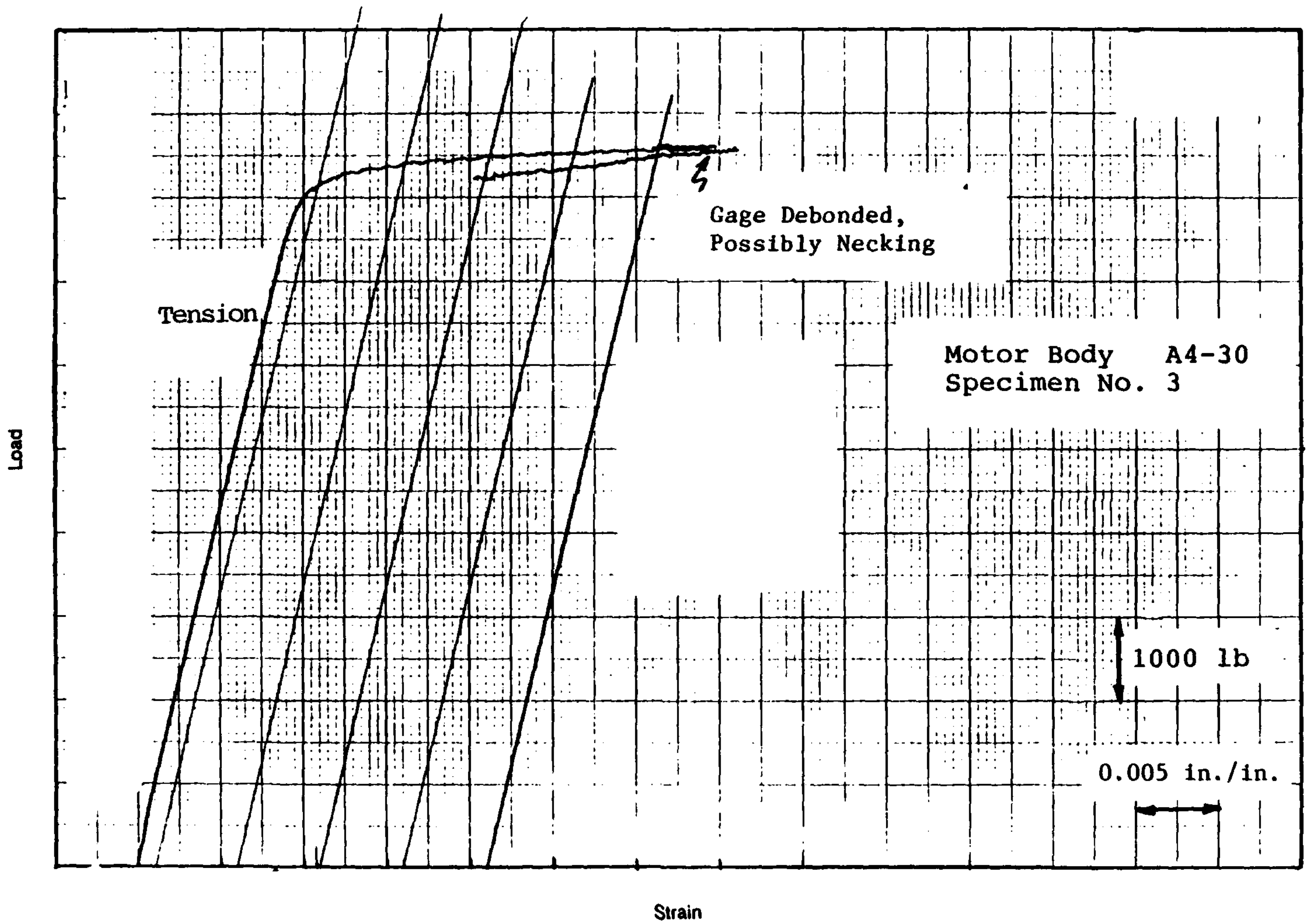


Figure A-3. Tension test (specimen no. 3).

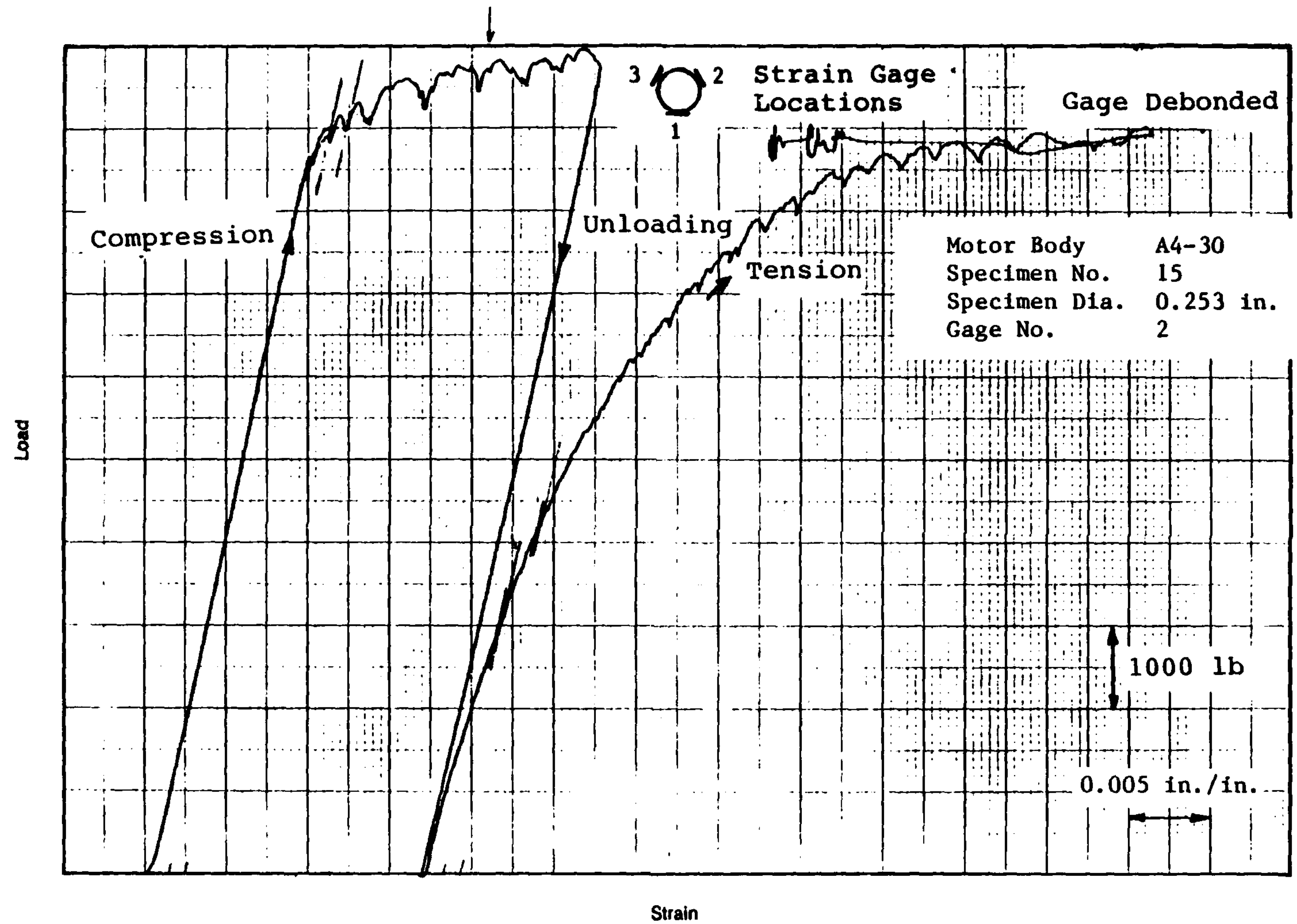


Figure A-4. Bauschinger effect test (specimen no. 15, gage no. 2).

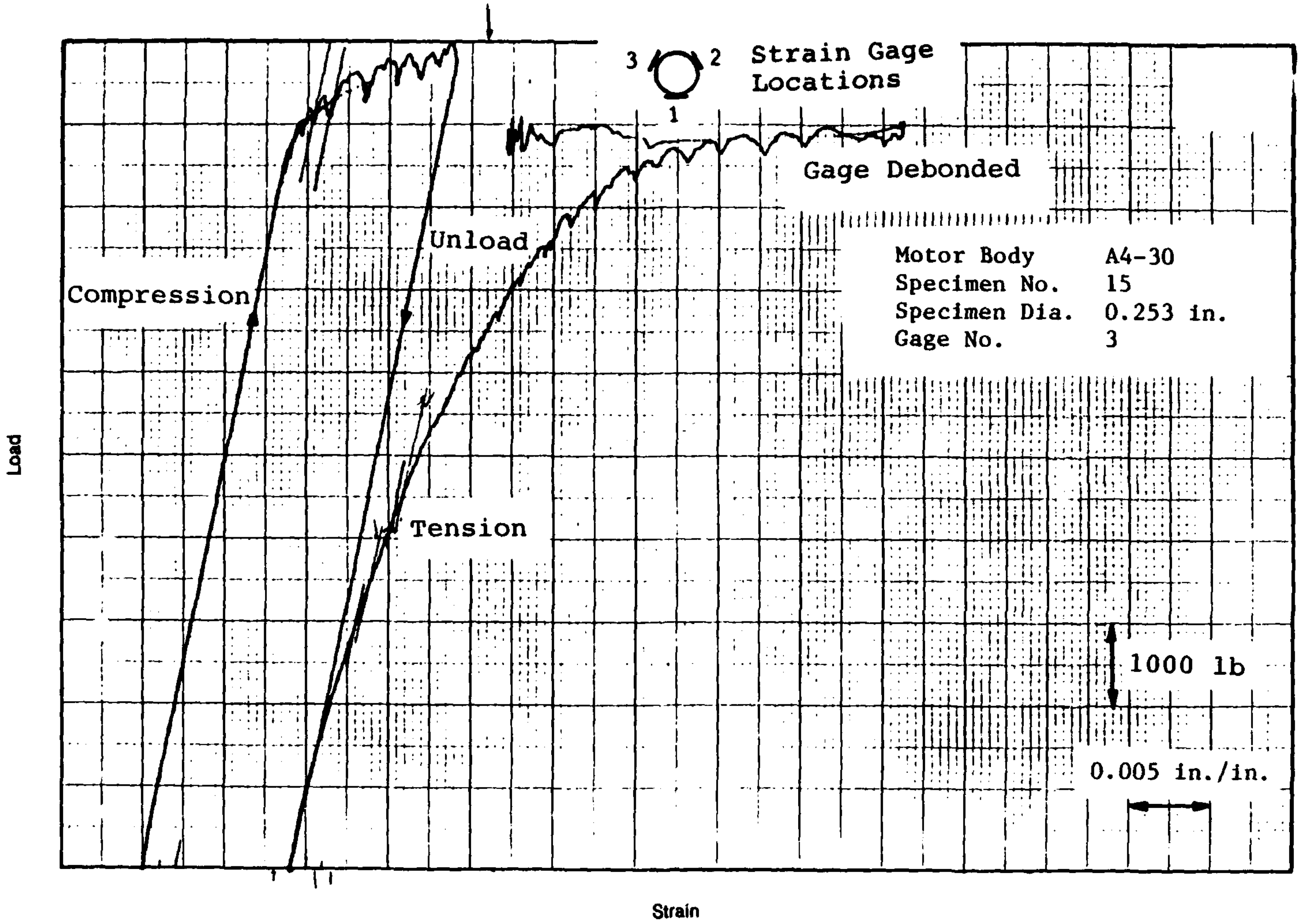


Figure A-5. Bauschinger effect test (specimen no. 15, gage, no. 3).

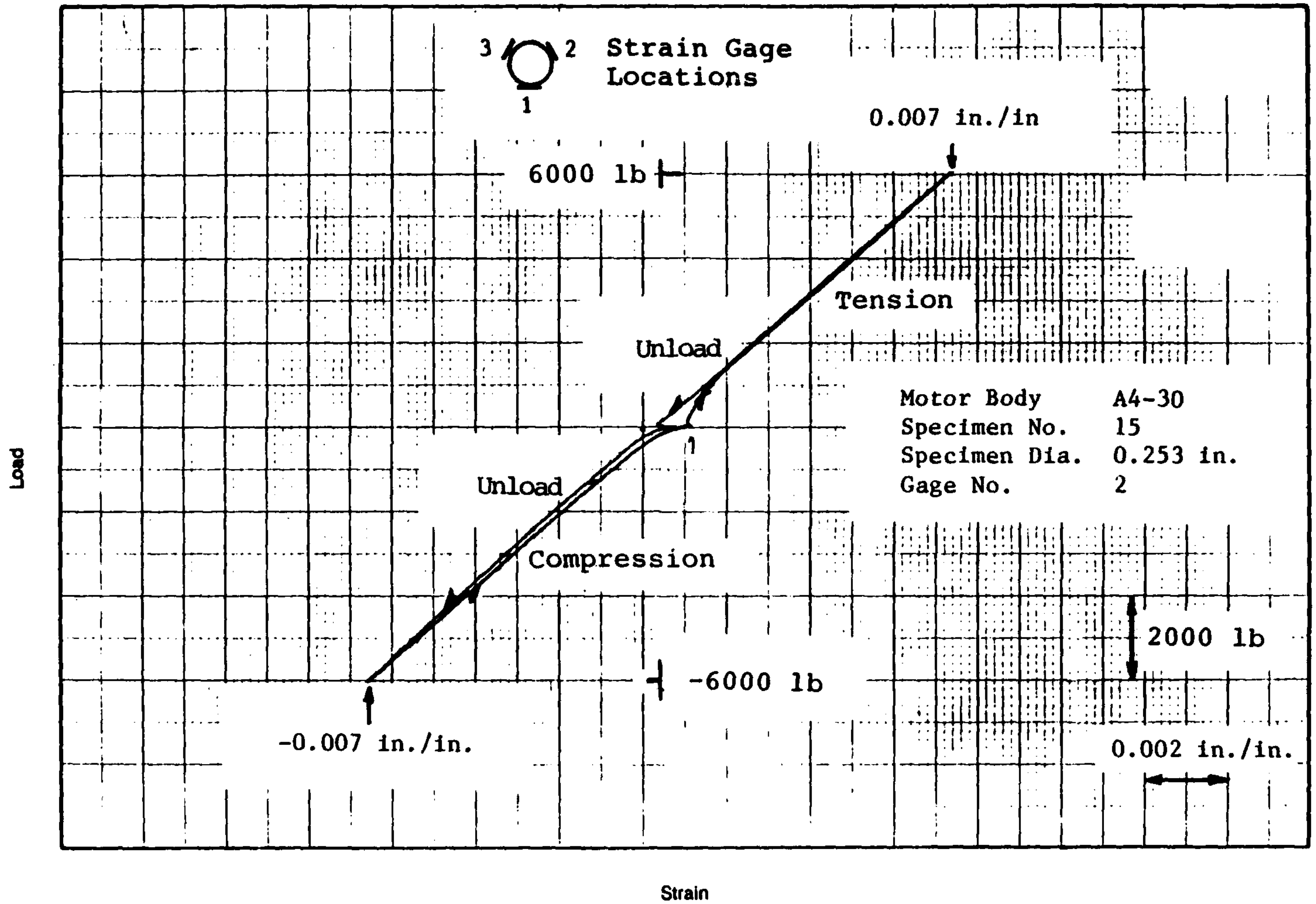


Figure A-6. Alignment check (specimen no. 15, gage no. 2).

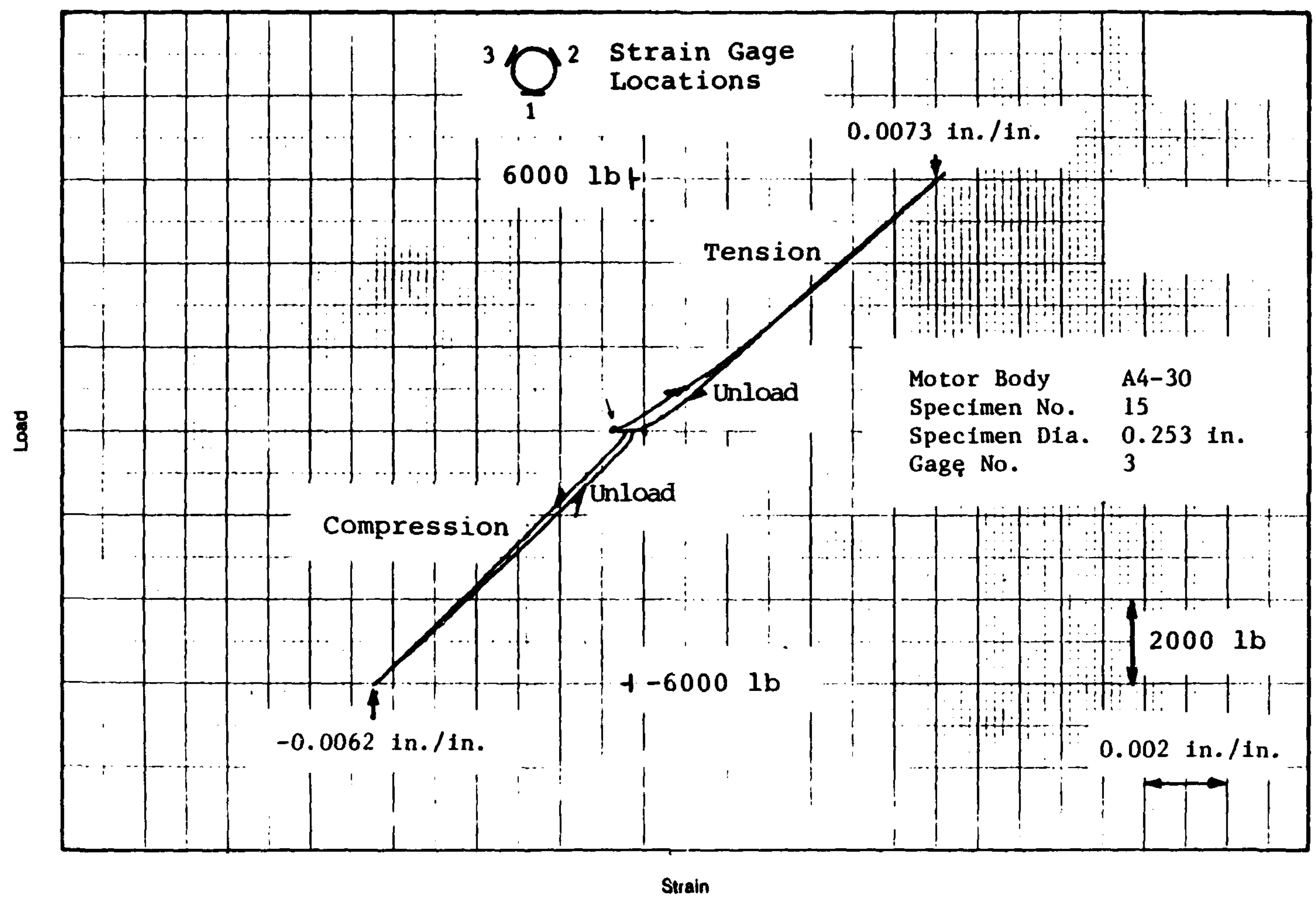


Figure A-7. Alignment check (specimen no. 15, gage no. 3).

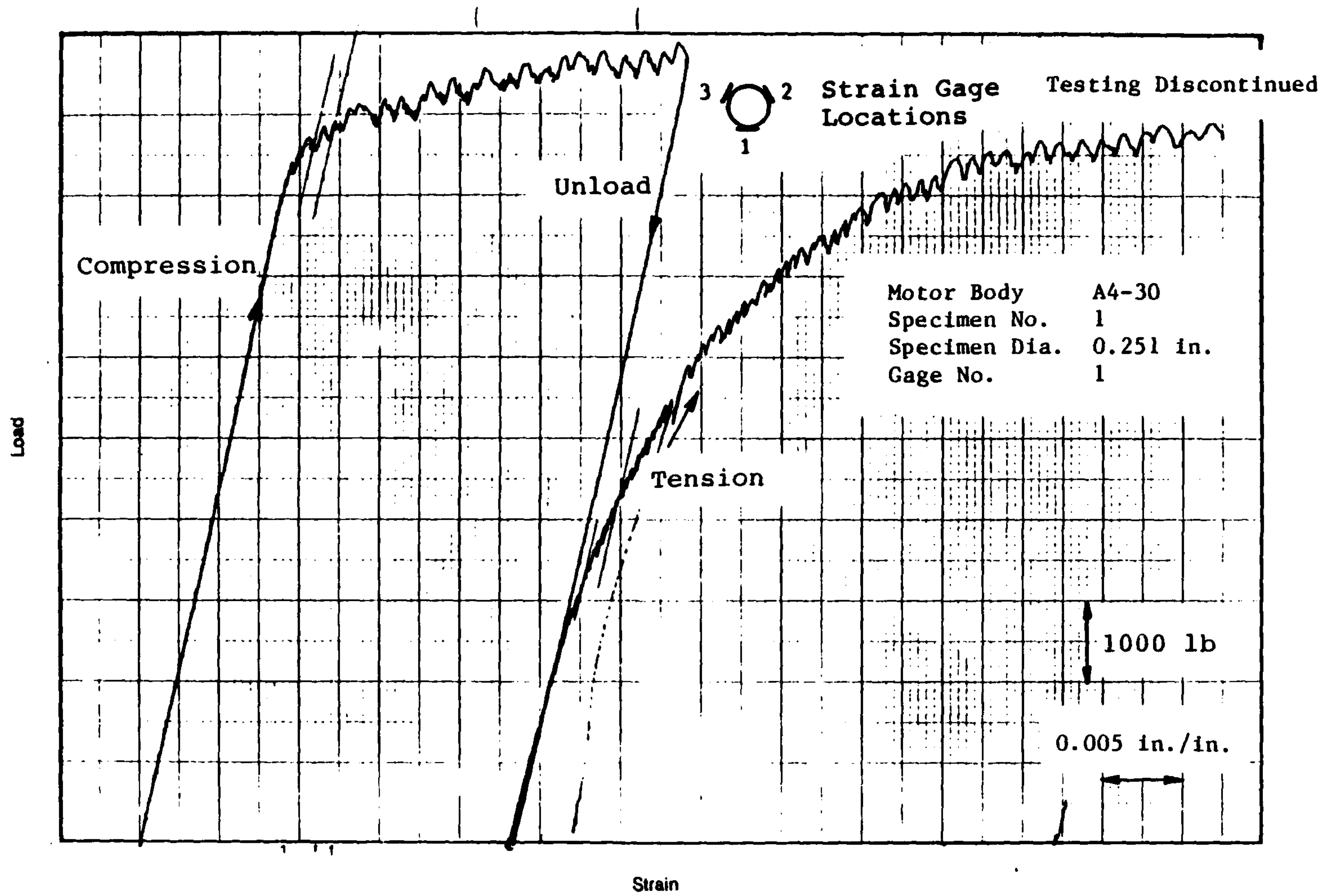


Figure A-8. Bauschinger effect test (specimen no. 1, gage no. 1).

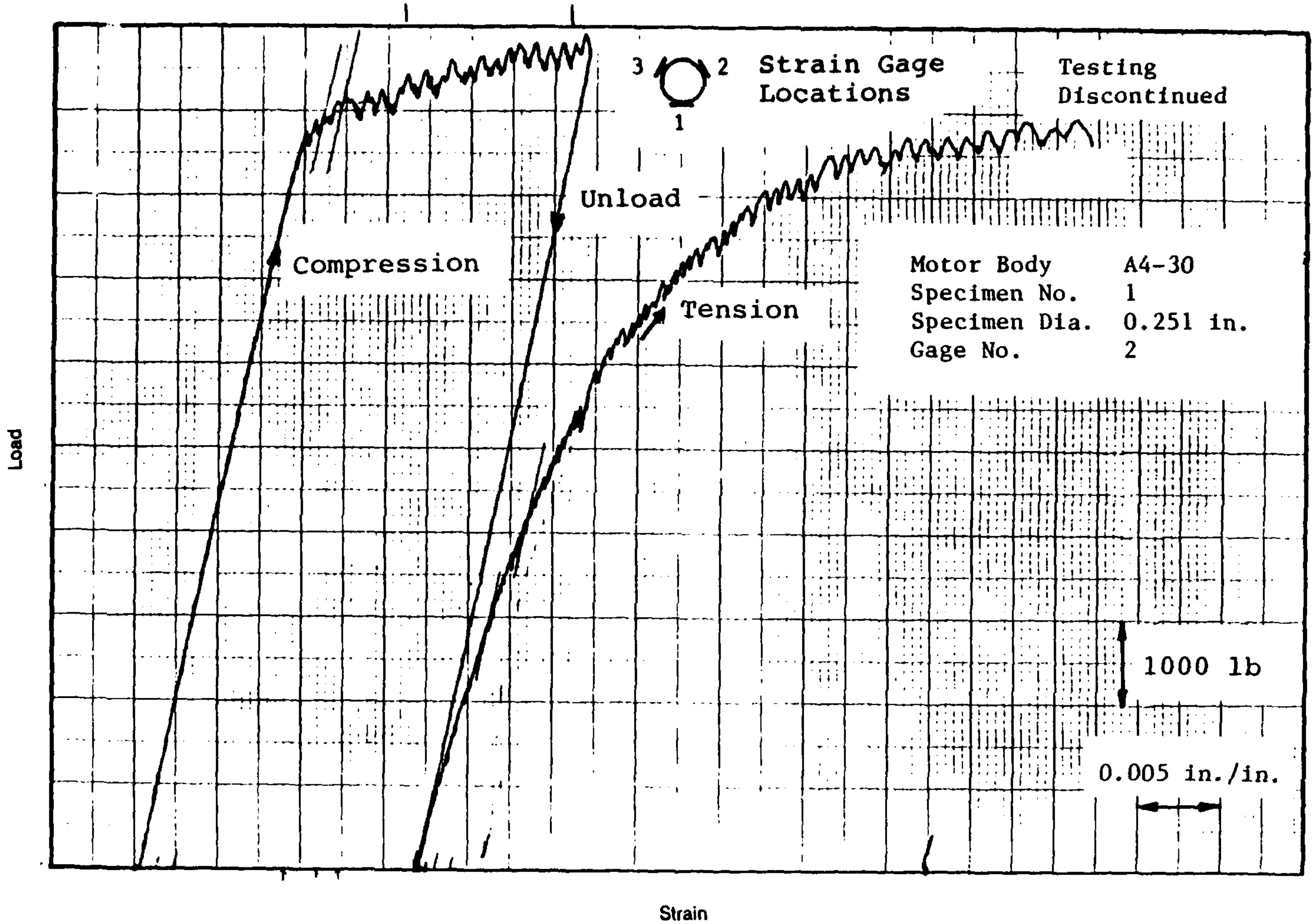


Figure A-9. Bauschinger effect test (specimen no. 1, gage no. 2).

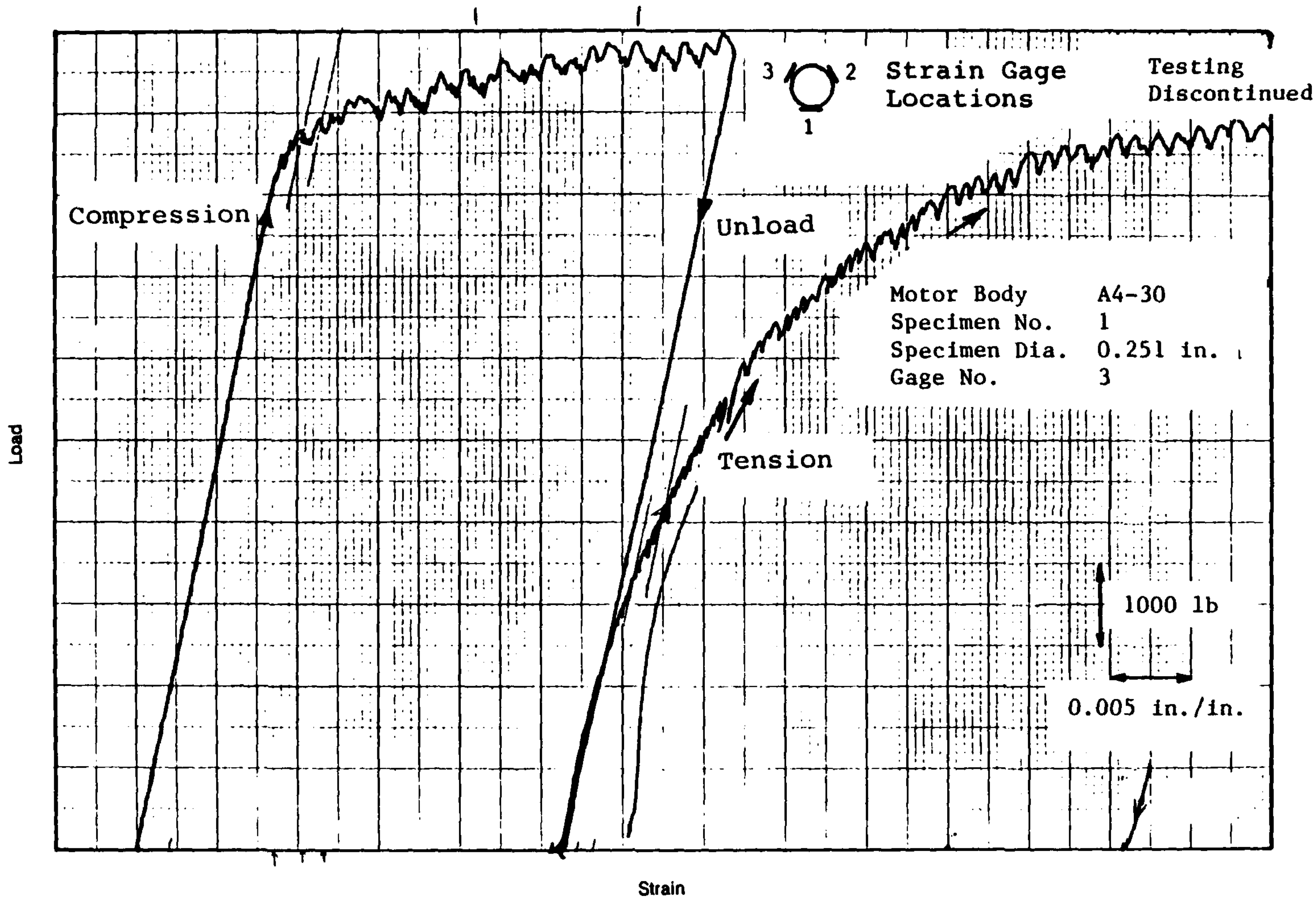


Figure A-10. Bauschinger effect test (specimen no. 1, gage no. 3).

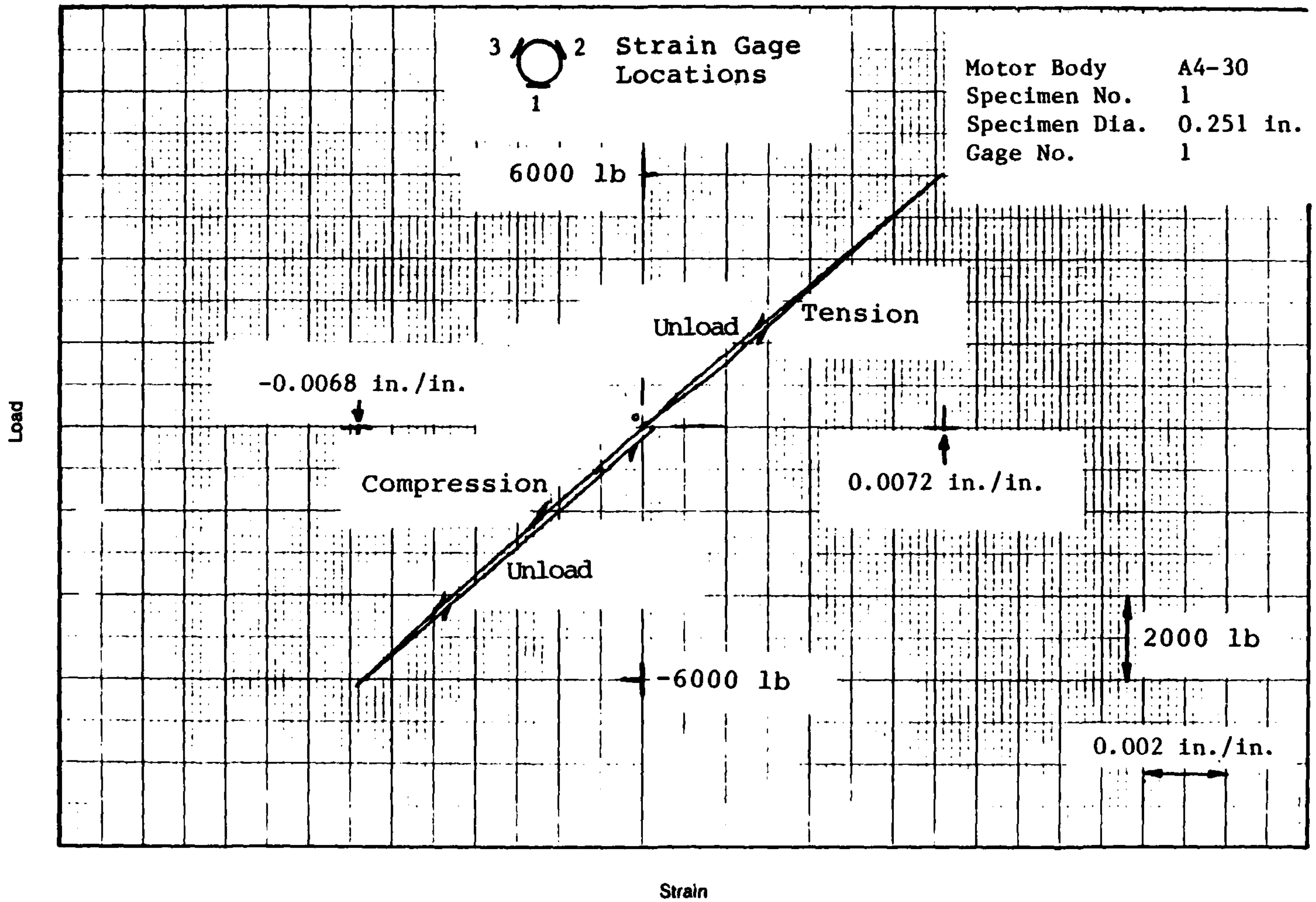


Figure A-11. Alignment check (specimen no. 1, gage no. 1).

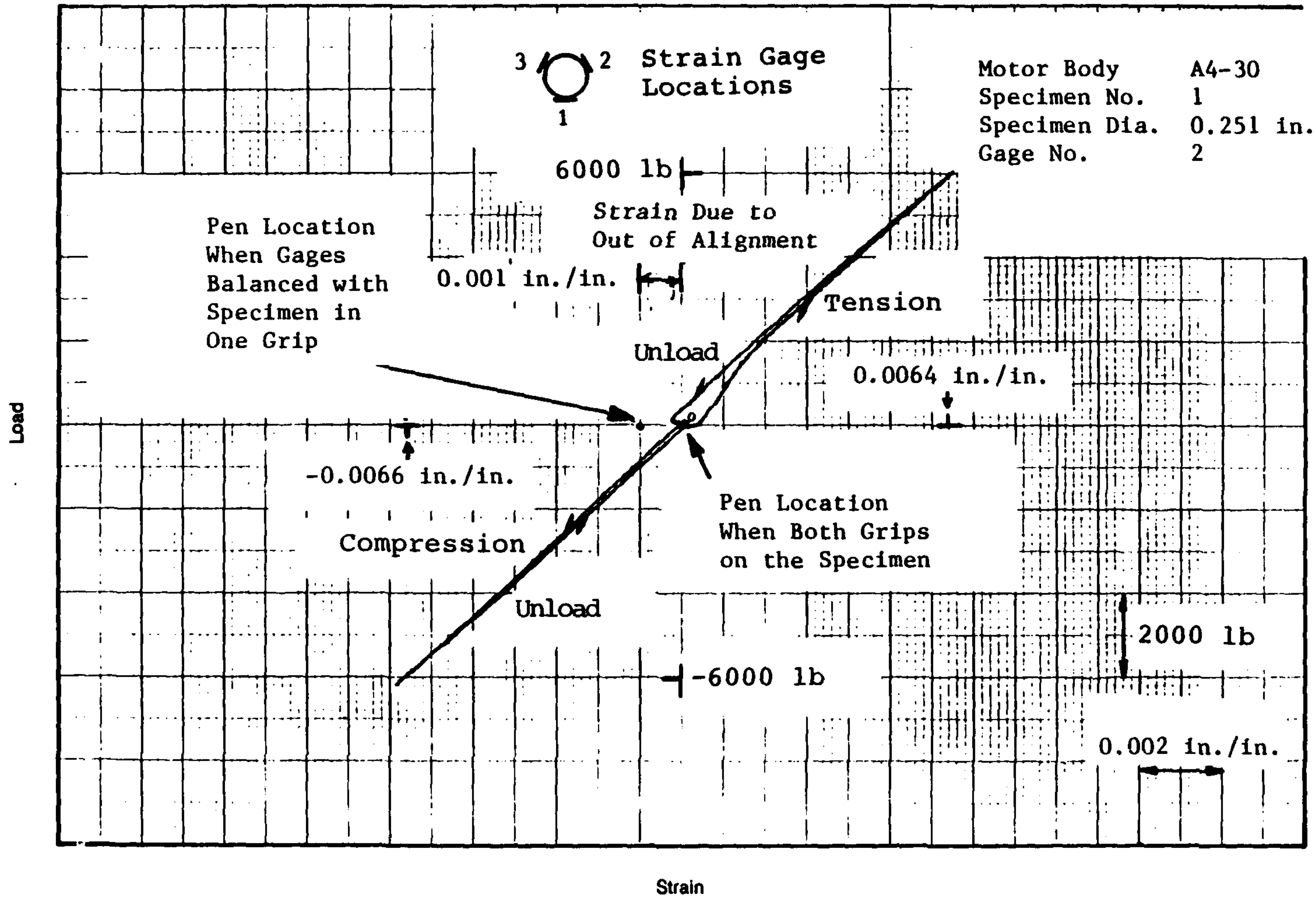


Figure A-12. Alignment check (specimen no. 1, gage no. 2).

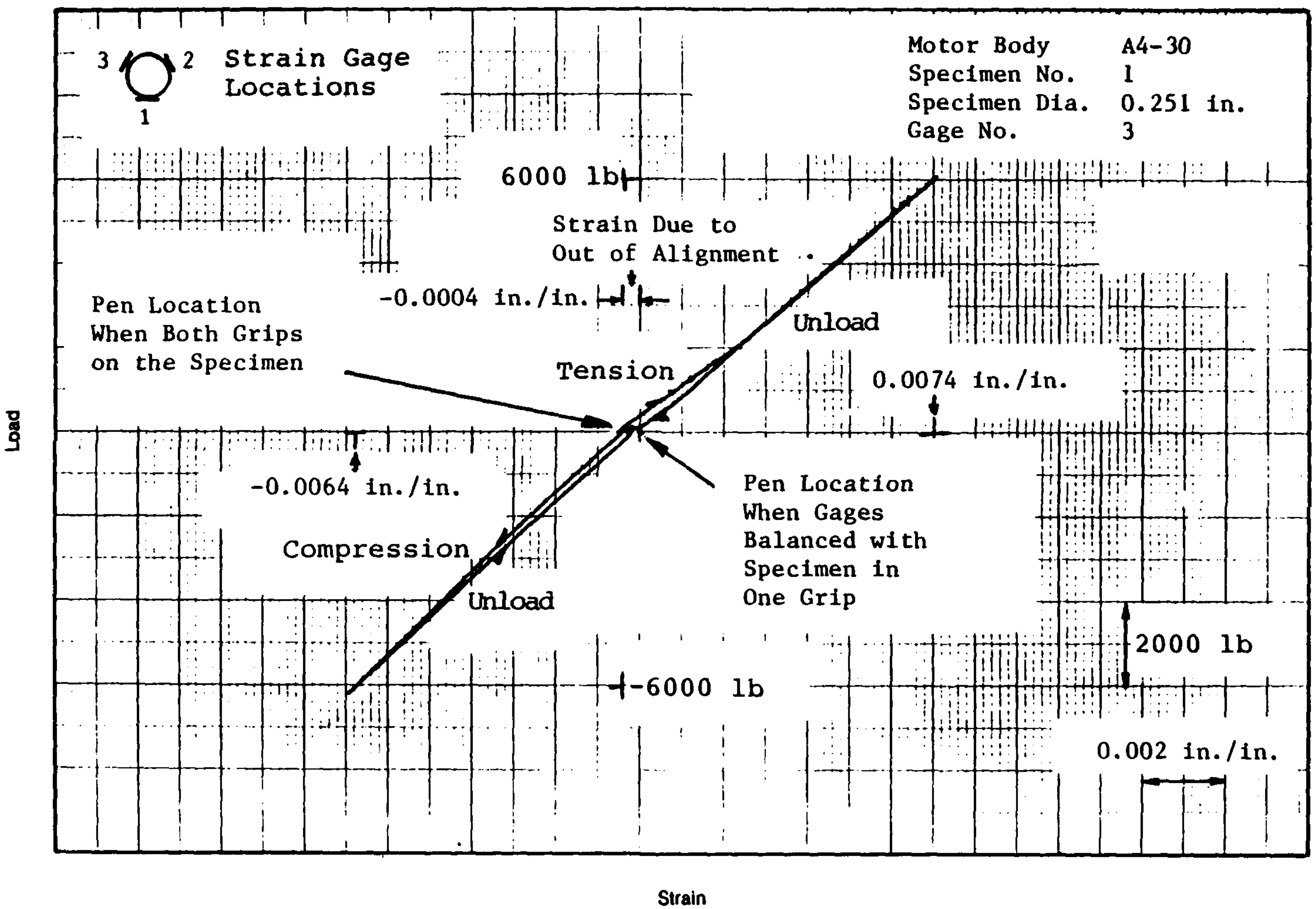


Figure A-13. Alignment check (specimen no. 1, gage no. 3).

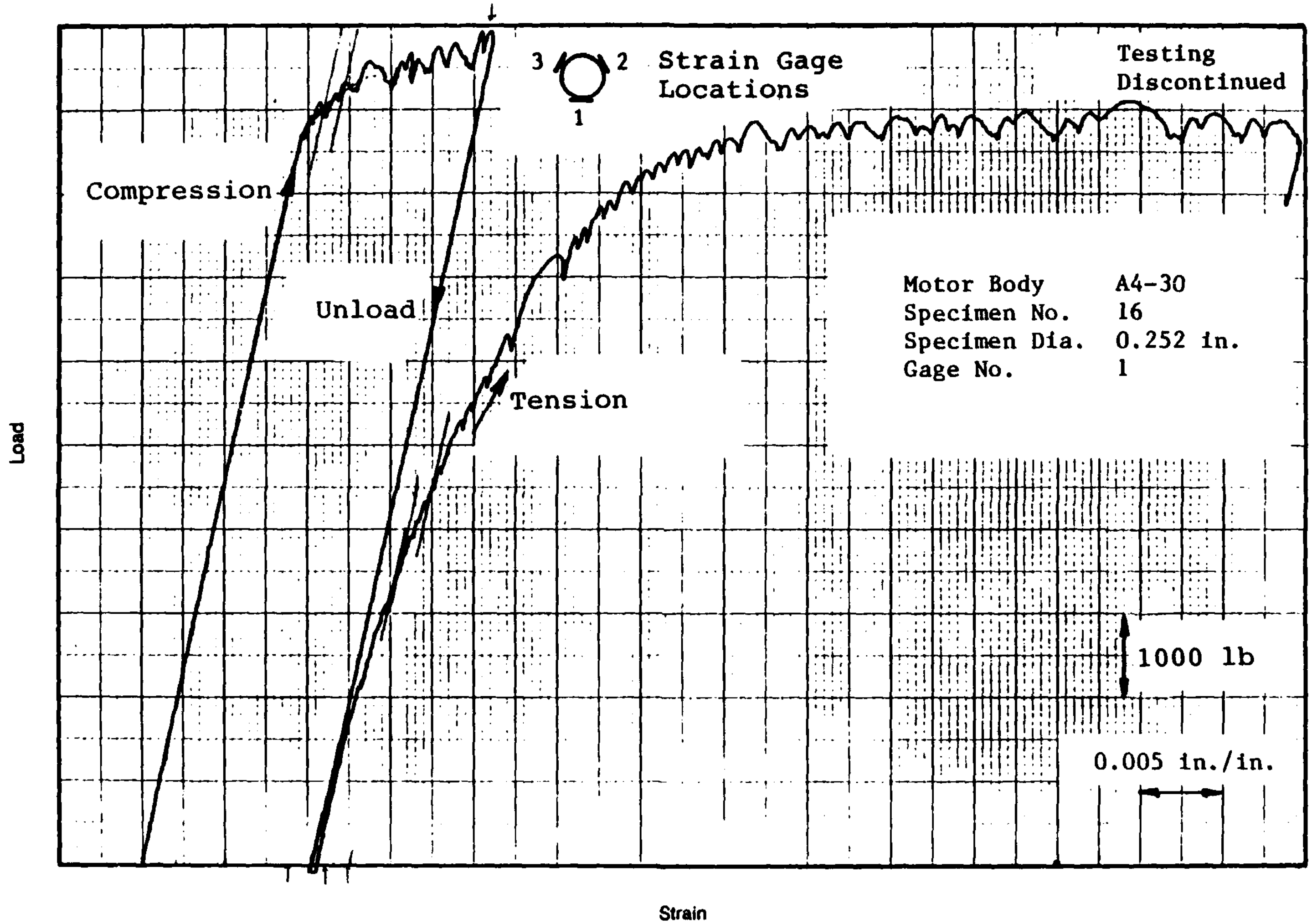


Figure A-14. Bauschinger effect test (specimen no. 16, gage no. 1).

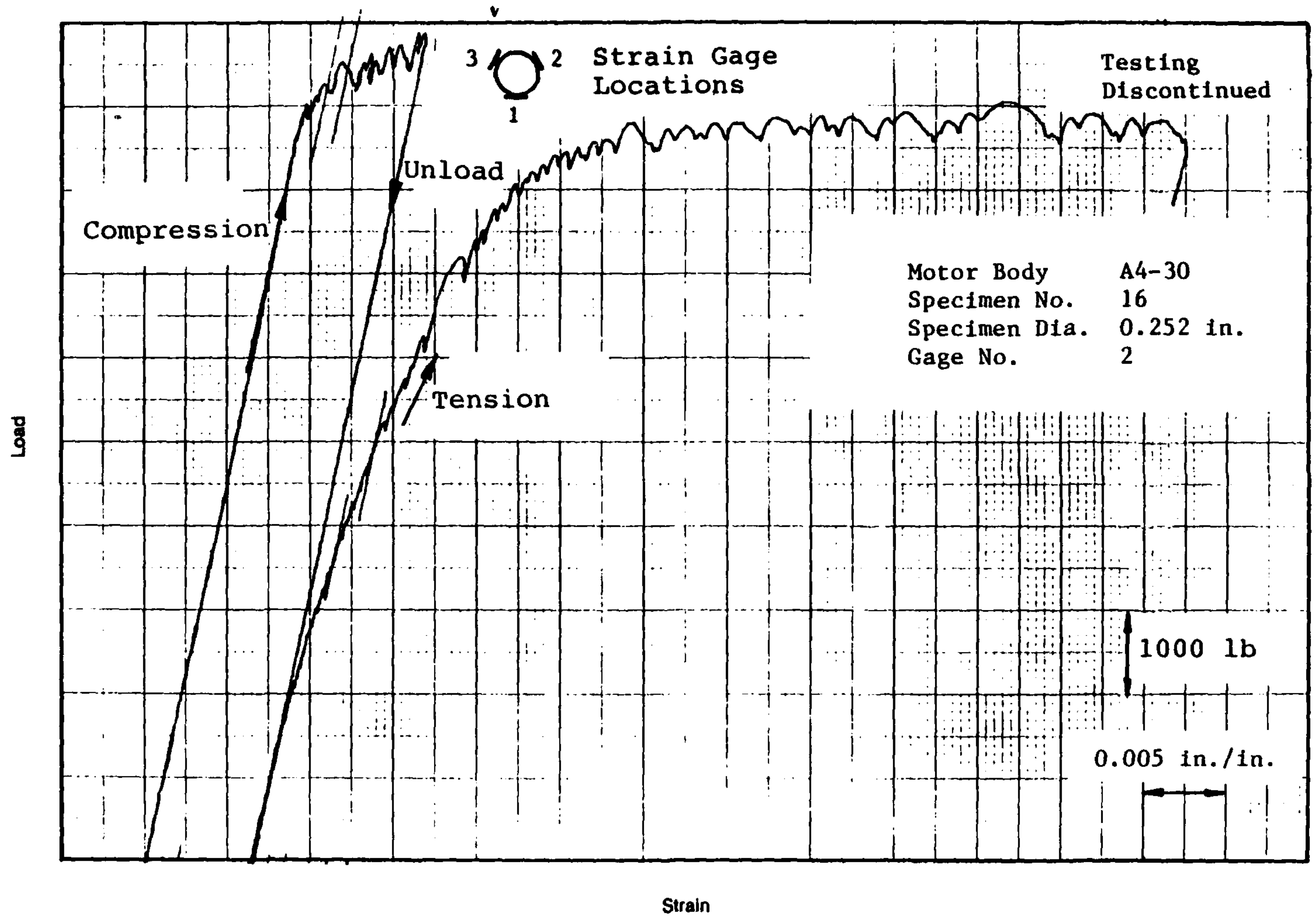


Figure A-15. Bauschinger effect test (specimen no. 16, gage no. 2).

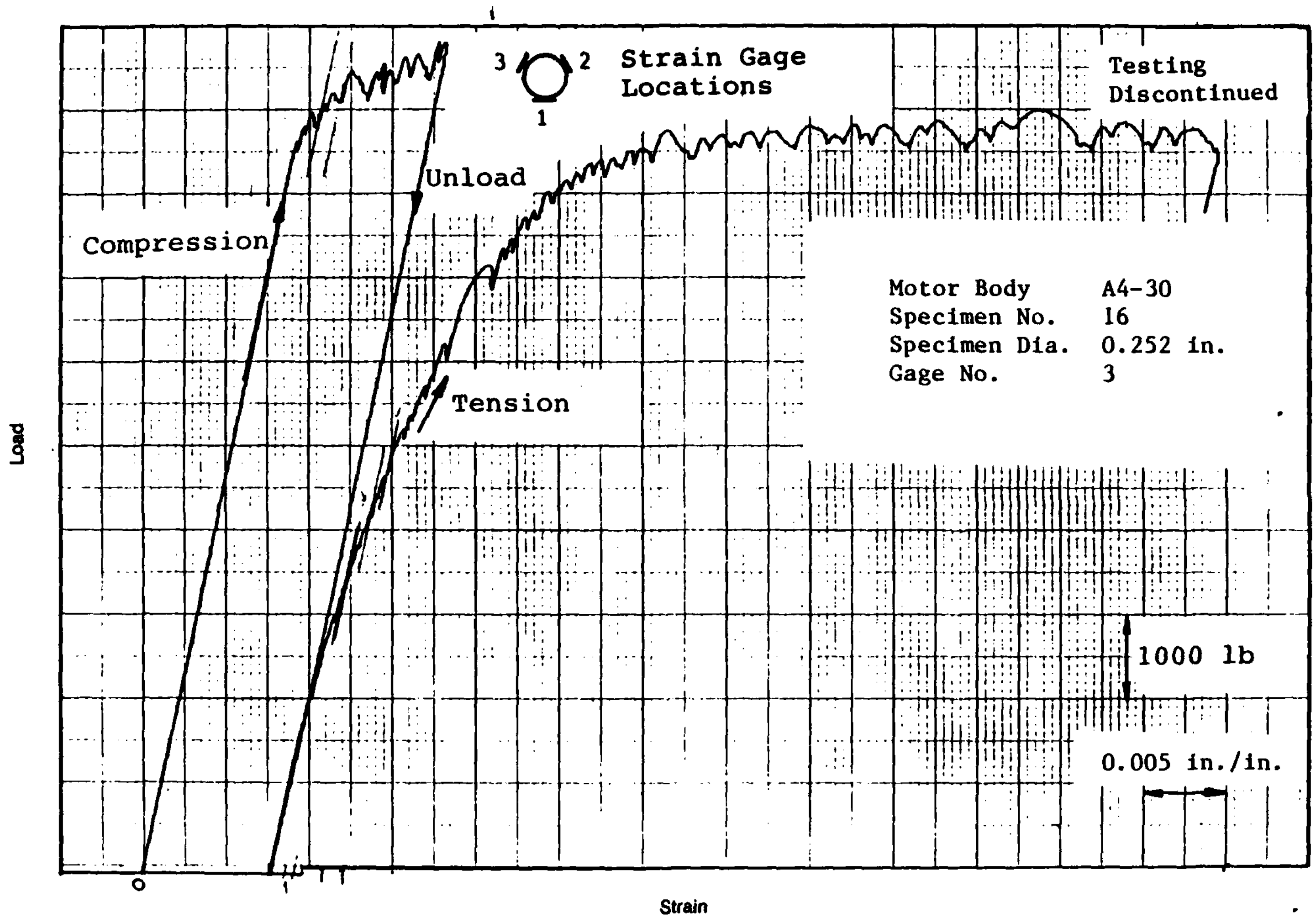


Figure A-16. Bauschinger effect test (specimen no. 16, gage no. 3).

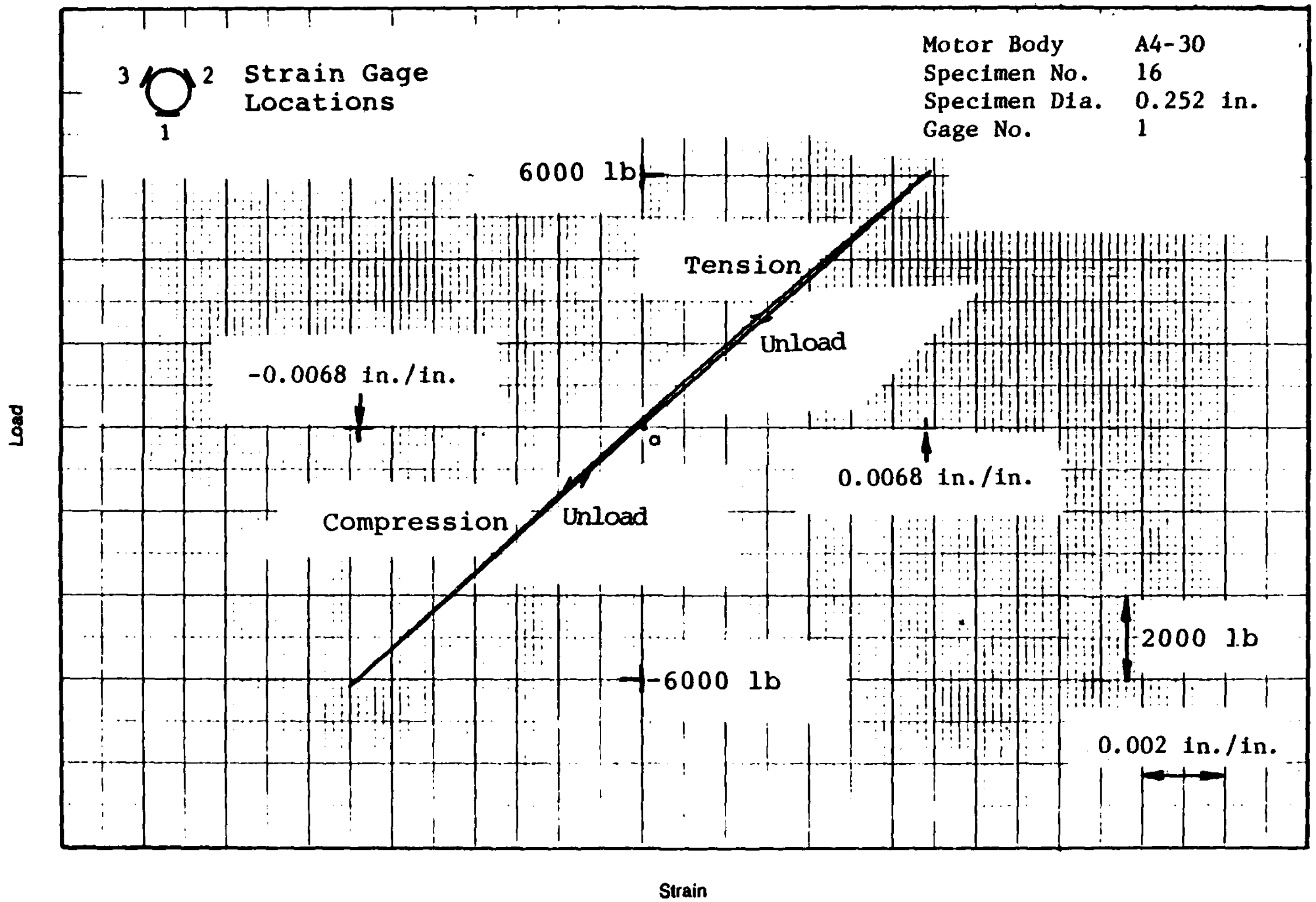


Figure A-17. Alignment check (specimen no. 16, gage no. 1).

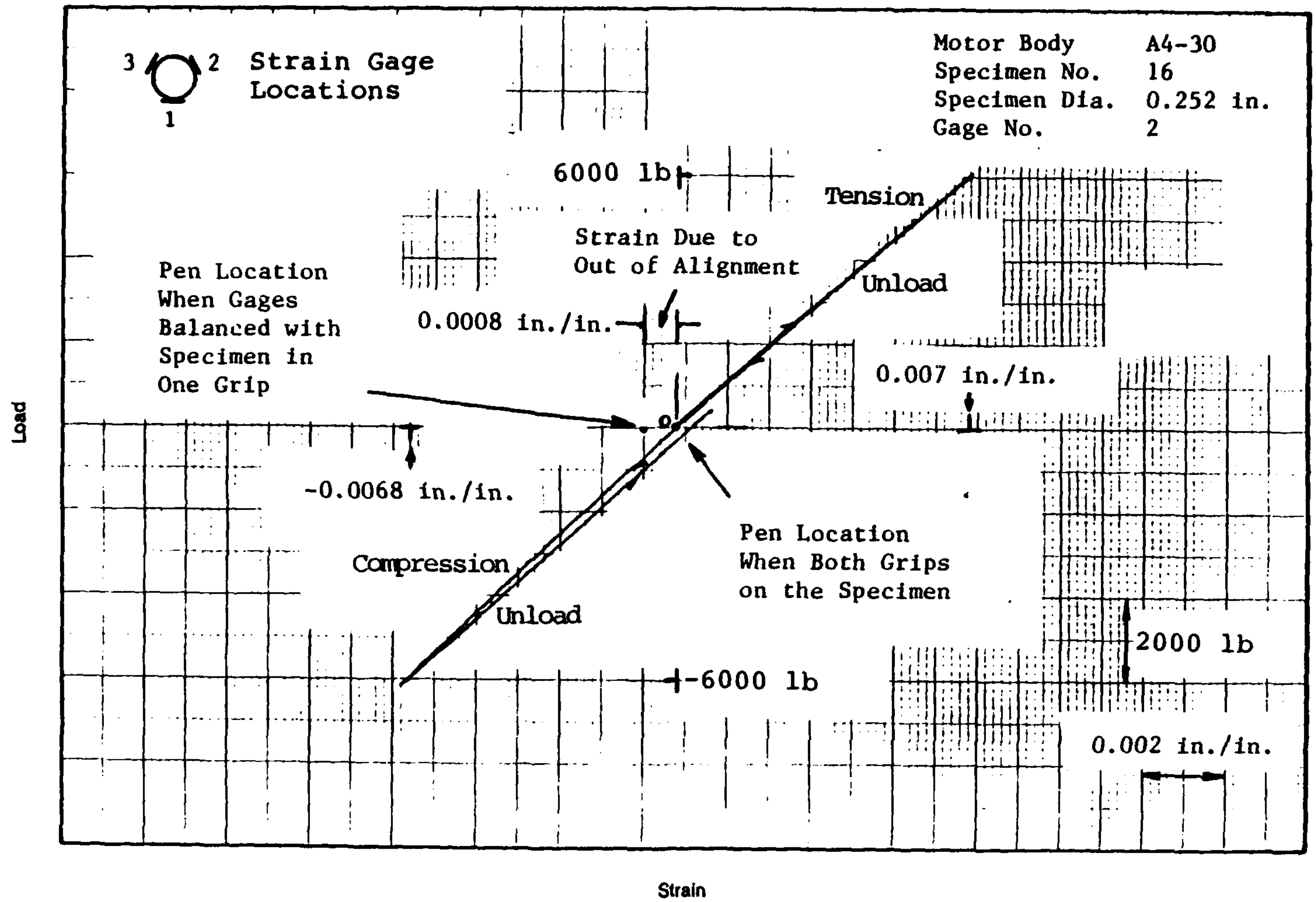


Figure A-18. Alignment check (specimen no. 16, gage no. 2).

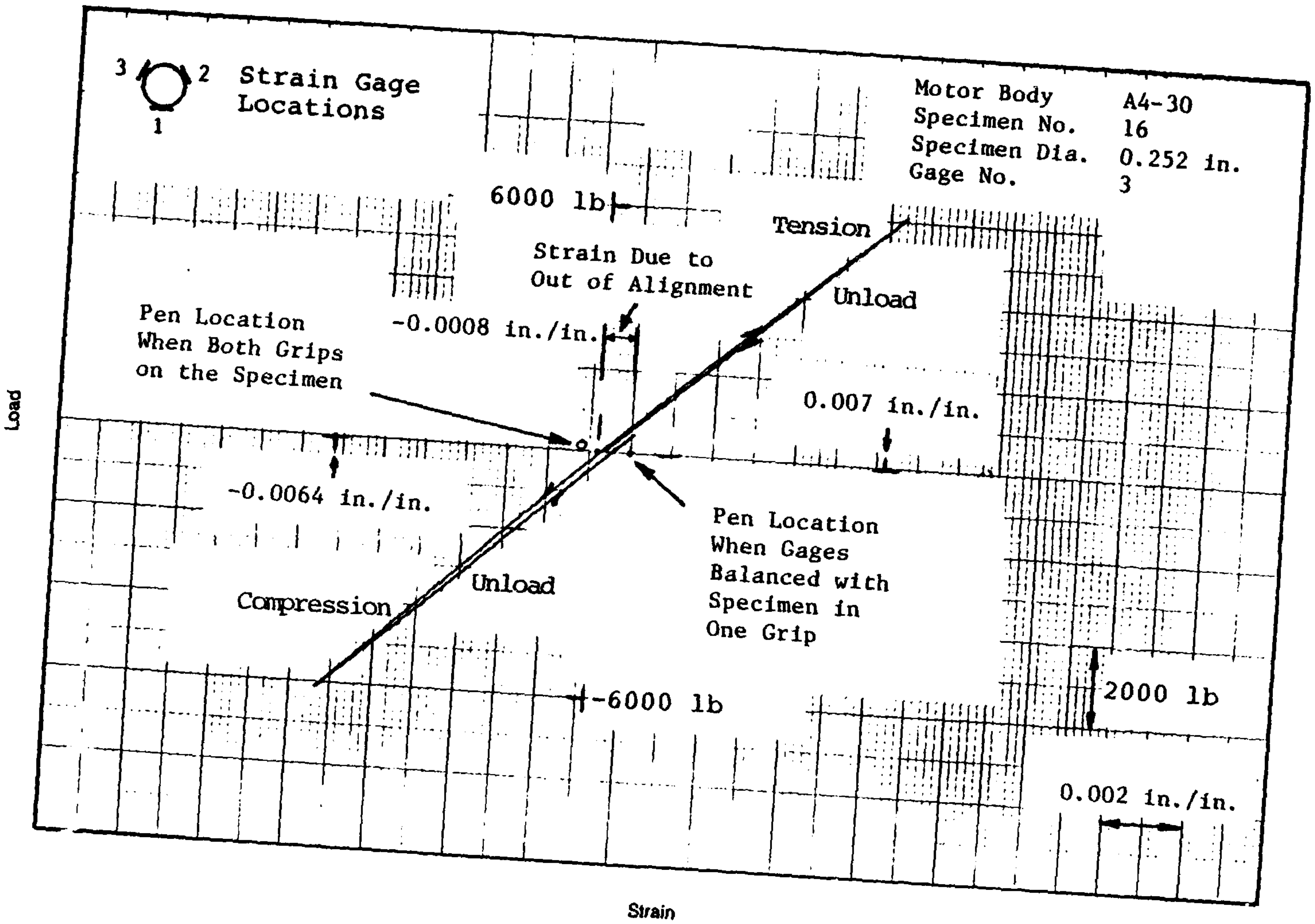


Figure A-19. Alignment check (specimen no. 16, gage no. 3).

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